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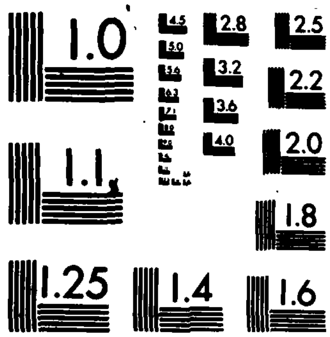
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Terrain Variables Improve Modeling of Richardson Numbers Less Than Unity in the Lower Atmosphere

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22 August 1983

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AIR FORCE SYSTEMS COMMAND, USAF

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20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

Occurrences of turbulence based on a critical Richardson number, obtained using data from nine rawinsonde stations for the years 1971-1975, are compared to show evidence of mountain induced effects in the lower atmosphere. The nine stations were selected since they could be divided into three groups by latitude. Two of the stations in each group are located in the Midwestern Plains and the third in the Western Mountain Region. Results from these comparisons led to the creation of a variable to indicate station terrain type for inclusion in an existing regression model. The improved model employing stepwise multiple

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regression techniques uses terrain, location, and seasonal information.

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1. INTRODUCTION

An attempt is made to develop regression terms and quantify the effects of mountain induced disturbances in the lower atmosphere. This information will be used to improve an existing model for predicting the occurrences of turbulence in the lower atmosphere. Murphy and Scharr[1] and Murphy et al[2] contain further explanation of the technique for determining turbulence estimates and the present model for predicting occurrences.

The gradient Richardson number, used as the dependent variable in the regression analysis, is

$$Ri = \frac{(g/T)\,[dT/dZ + \Gamma_d]}{(\partial V_x/\partial Z)^2 + (\partial V_y/\partial Z)^2}$$

where g is the acceleration of gravity, T is the absolute temperature, dT/dZ is the vertical temperature gradient, Γ_d is the dry adiabatic lapse rate (9.7° K/km) and the denominator is the square of the vertical shear of the horizontal wind.

(Received for publication 16 August 1983)

1. Murphy, E.A., and Scharr, K.G. (1981) Modeling Turbulence in the Lower Atmosphere Using Richardson's Criterion, AFGL-TR-81-0349, AD A115244.
2. Murphy, E.A., D'Agostino, R.B., and Noonan, J.P. (1982) Patterns in the Occurrences of Richardson Number Less Than Unity in the Lower Atmosphere, J. Appl. Meteorol. 21:321-333.

Rawinsonde measurements of wind and temperature as a function of altitude are used to determine Richardson numbers. The Richardson number values as a function of altitude are calculated at 1-km levels from 2 km to 30 km for each of two daily height profiles of wind and temperature. This provides from 100 to approximately 180 values of Ri for each altitude bin per season. The percent occurrence of Ri ≤ 1.0 is obtained by taking the ratio of the number of occurrences of Ri ≤ 1.0 to the total number of measurements per season. The likelihood of occurrence of turbulence is then based on the relative frequency of occurrence of a critical Richardson number ($Ri_c = 1.0$).

The present model for predicting turbulence has been established for the following ranges: lower range (2-7 km), middle range (8-13 km) and upper range (14-19 km). Model variables include location type (latitude, longitude, altitude), transformations of them (lat^i, $long^j$, alt^k; i, j=0, 1, 2,; k=0, 1, 2, 3), cross products terms ($lat^i \times long^j \times alt^k$) and seasonal indicators. The dependent variable, an indicator of turbulence, is based on percent occurrences of the Richardson number less than unity. By simply using location and seasonal information we have been able to explain a substantial amount of the variation in the turbulence indicator (38% in the lower range, 61% in the middle range, and 42% in the upper range). This has been done for a sample 21 stations chosen representative of the continental United States. Also, another important result of that study is that yearly variations in the occurrences of Ri_c are found to be small (less than 1% of the total variation). Evidence of mountain induced disturbances are presented and improvements are made in the model through the use of terms to quantify terrain aspects.

2. EVIDENCE OF MOUNTAIN INDUCED DISTURBANCES – COMPARISON OF DATA SETS

A qualitative analysis performed on many of the data reporting stations (81 in the continental United States) revealed that the height profiles of percent occurrences of Ri ≤ 1.0 for stations in the proximity of mountain ranges are markedly different from those stations in the plains areas of the United States. This was noted from visual observation of microfiche computer plots.

Three sets of data are used to describe mountain induced disturbances in the atmosphere. Each set consists of three stations at nearly the same latitude. In each set, two measuring stations are in the midwestern plains and one is in the western mountain region. The one exception to this is Chatham, Massachusetts, which is considered here a plains station. Only nine stations from the 81 stations in the continental United States are suitably located to provide this kind of comparison. In the first set, Figure 1, the three stations used for comparison are within

approximately 2 degrees of latitude. The two plains stations, Sault St. Marie, Michigan and International Falls, Minnesota are plotted together in Figure 1a. The degree of closeness of fit for the two profiles of percent occurrence of Ri $\leq$ 1 are evident. This is true for all four seasons. Note that the profiles for each season are for the five year averages (1971-1975). Each of the years compared separately are also close. This is true since, as was previously stated, the yearly contribution to variation in percent occurrence of turbulence (using Ri_c as an indicator) was found by regression to be less than one percent. The higher percent occurrences for the mountain site, Great Falls, Montana, shown in Figure 1b, continues up to approximately 15 km. In fact, percent occurrences are consistently higher in all of the five years from 1971-1975.

The two plains stations of the second set, Topeka, Kansas and Dayton, Ohio are plotted together in Figure 2a. The mountain station for this set is Denver, Colorado, which is plotted for comparison along with Topeka, Kansas, in Figure 2b. Here again there is fairly good agreement between the two plains stations, whereas there are differences as high as 25% between the plains and mountain stations. These differences are found as high as 8 km. The three stations in this set are located within a degree of latitude.

In the third set, the three stations are separated by just over one degree in latitude. The plains stations, Chatham, Massachusetts, and Flint, Michigan, are plotted together in Figure 3a and are remarkably close. In comparison, the percent occurrences of the mountain station, North Platte, Nebraska (Figure 3b) are seen to be markedly higher than the plains station, Flint, Michigan. This is true up to a height of 5 km.

3. TERRAIN EFFECTS ANALYSIS – STATISTICAL APPROACH

Appropriate statistical techniques were employed to determine significance and to develop the improved model. Using the 21 stations that determined the original model, the following points are considered in an effort to quantify the terrain effects:

(a) Classification of terrain features,

(b) Creation of terrain type variables,

(c) Determination of effects.

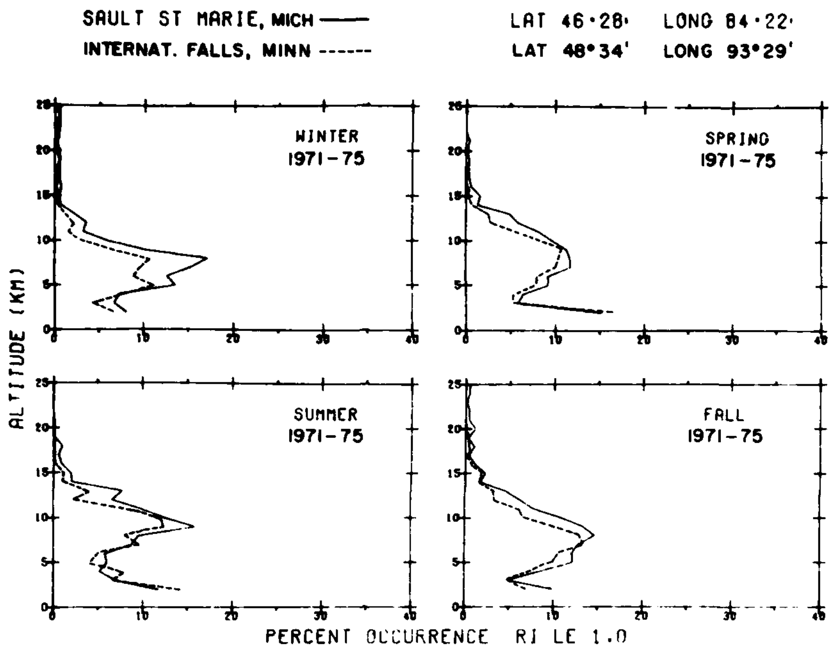

Figure 1a. Mean Seasonal Occurrences of Turbulence (based on $Ri_c \leq 1.0$) for Two Plain Stations Near 48° N Latitude

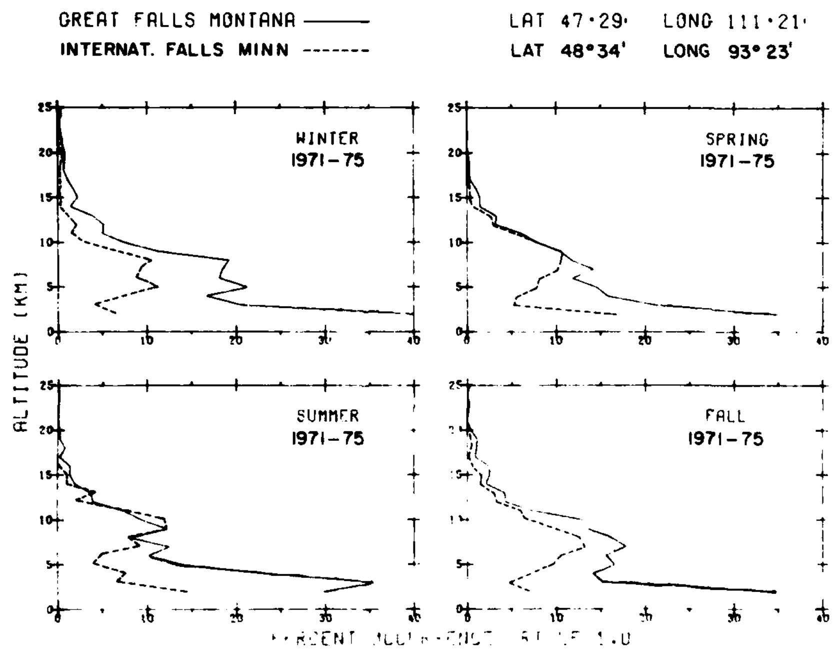

Figure 1b. Comparison of Mean Seasonal Occurrences of a Plains Station in Figure 1a With a Mountain Station Near 48° N Latitude

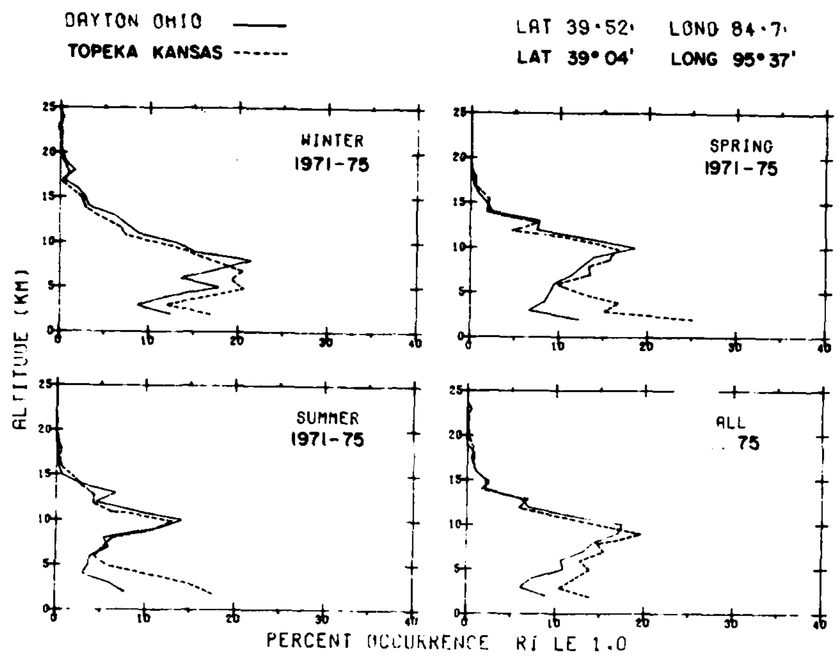

Figure 2a. Mean Seasonal Occurrences of Turbulence (based on $Ri_c \leq 1.0$) for Two Plains Stations Near 38° N Latitude

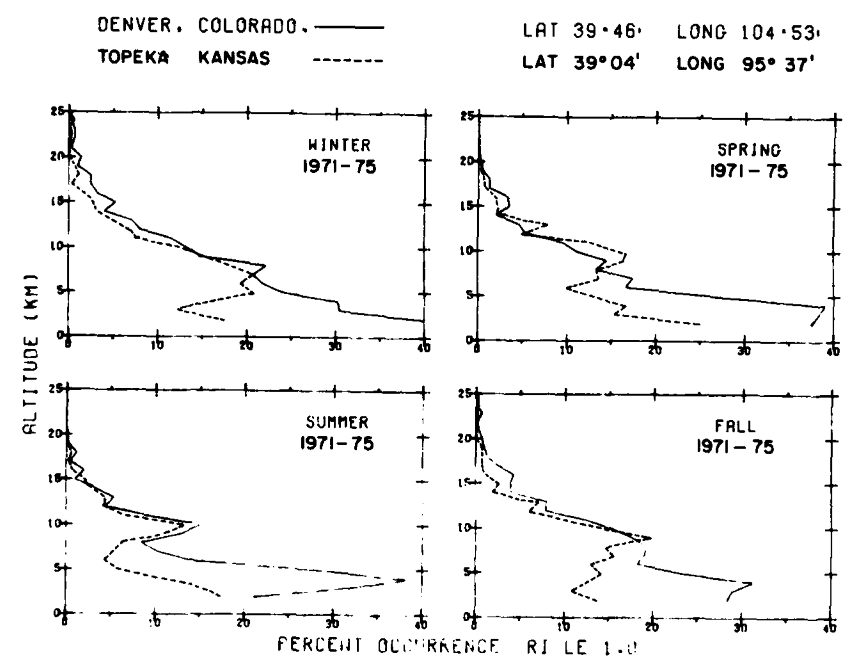

Figure 2b. Comparison of Mean Seasonal Occurrences of a Plains Station in Figure 2a With a Mountain Station Near 38° N Latitude

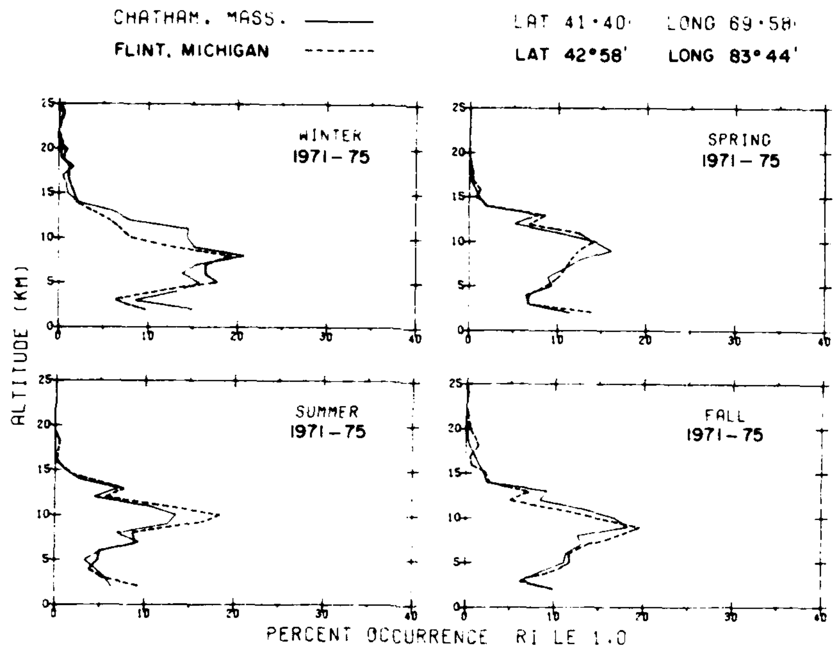

Figure 3a. Mean Seasonal Occurrences of Turbulence (based on $Ri_c \leq 1.0$) for a Plains Station (Flint, MI) and a Coastal Station (Chatham, MA) Near 42° N Latitude

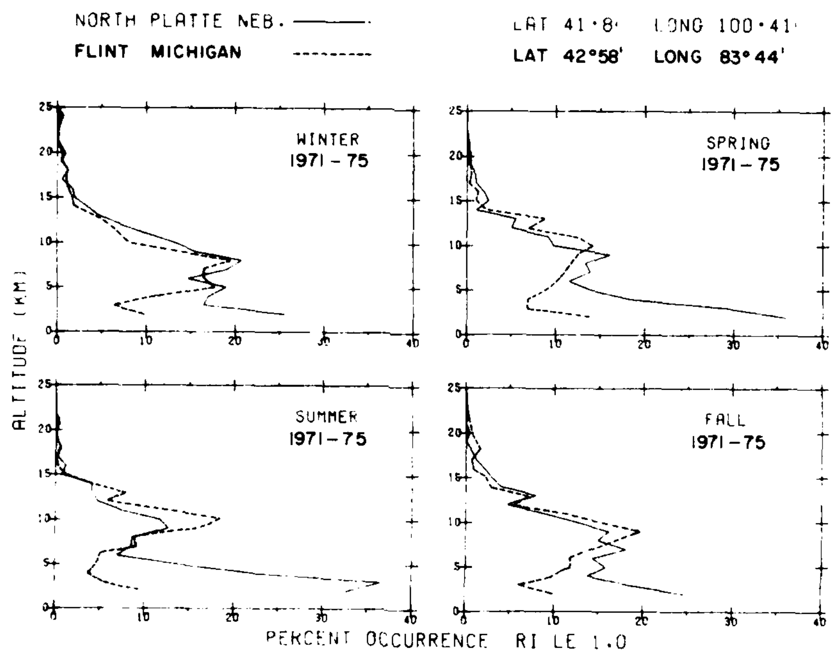

Figure 3b. Comparison of Mean Seasonal Occurrences of the Plains Station in Figure 3a With a Mountain Station Near 42° N Latitude

3.1 Classification

It is apparent from a topographic map of the United States that there are three types of general terrain. The coastal sealevel areas, the central plains section and the mountain regions. Classification of a station terrain type was determined by examining the topography within a radius of 160 km of the station location. To determine if terrain effects were significant, a two-way analysis of variance (ANOVA) test was performed for each altitude bin.[3] The range of the mean differences in turbulence within each altitude bin for the different terrain groups was of interest. This statistical test examines mean differences between groups using the test statistic F. Results of the two-way ANOVA on the 2-7 km and 8-13 km bins are presented (Table 1). Examination of the F-statistic reveals that there are overall significant differences ($p << 0.001$) between the defined terrain groups (Table 2).

Table 1. Two-Way Analysis of Variance Results

2-7 km	df	Winter	Spring	Summer	Fall
Terrain	2, 108	10.91* (7.41)**	4.99 (7.41)	28.28 (7.41)	24.54 (7.41)
Alt. Level	5, 108	4.78 (4.48)	9.87 (4.48)	5.50 (4.48)	4.77 (4.48)
8-13 km					
Terrain	2, 108	30.42 (7.41)	36.78 (7.41)	6.72 (7.41)	15.38 (7.41)
Alt. Level	5, 108	28.17 (4.48)	28.17 (4.48)	28.27 (4.48)	58.38 (4.48)

Two-way analysis of variance is used to test the hypothesis of the existence of mean differences between groups. A significant difference between groups, at the α level, is denoted by $F_{calculated} > F^{[\alpha]}_{critical}$. Examination of this table reveals that there are significant differences between the three categories for both the 2-7 and 8-13 km bins.

*Calculated F-value (** Critical F-value for p = 0.001).

3. Draper, N. R., and Smith, H. (1981) Applied Regression Analysis, 709 pp., John Wiley, New York.

Table 2. Station Categories

Sealevel	Plains	Mountain
Brownsville, TX	Dayton, OH	Denver, CO
Chatham, MA	Flint, MI	Great Falls, MN
Miami, FL	Glasgow, MT	Medford, OR
Portland, ME	Green Bay, WI	Salem, OR
Washington, D.C.	Greensboro, NC	Spokane, WA
Waycross, GA	International Falls, MN	Winslow, AZ
	North Platte, NE	
	Sault Ste. Marie, MI	
	Topeka, KS	

3.2 Creation of Terrain Variables

In order to include the effects of terrain in the model, two variables were created to indicate the type of terrain:

$$\text{Sealevel} \begin{cases} 1 \text{ if station is in sealevel category} \\ 0 \text{ otherwise} \end{cases}$$

$$\text{Mountain} \begin{cases} 1 \text{ if station is in mountain category} \\ 0 \text{ otherwise} \end{cases}$$

A plains station would then be indicated by sealevel = 0 and mountain = 0. A multiple stepwise least squares regression procedure was employed to determine the significance of terrain differences on turbulence. The set of independent variables which are candidates for entry into the turbulence model include the previous terms from the existing model plus sealevel and mountain terms. Based on the ANOVA results, the regions 2-7 km and 8-13 km were selected for modeling.

3.3 Determination of Effects

In the 2-7 km range, the multiple correlation coefficient squared (R^2) increased by nearly 10% over the model without terrain indicators. Thus a significant improvement in the turbulence model is represented.

There was a negligible contribution to turbulence explained in the 8-13 km model using the terrain indicator variables. This was true even though the ANOVA test in that range determined significant differences between terrain groups. The explanation for this is that turbulence variations due to differing terrain types occur

at varying altitudes in the 8-13 km range thus accounting for the ANOVA results. Because there is no sustained effect at any given altitude, the terrain variables do not add significant information to explain turbulence in the 8-13 km bins. Occurrences of turbulence estimates, based on a critical Richardson number of 1.0, are shown in comparison to model predicted values in Figure 4. These results from three representative stations, two in the mountain and one in the plains region, clearly demonstrate the improvements in the model with the added terrain terms.

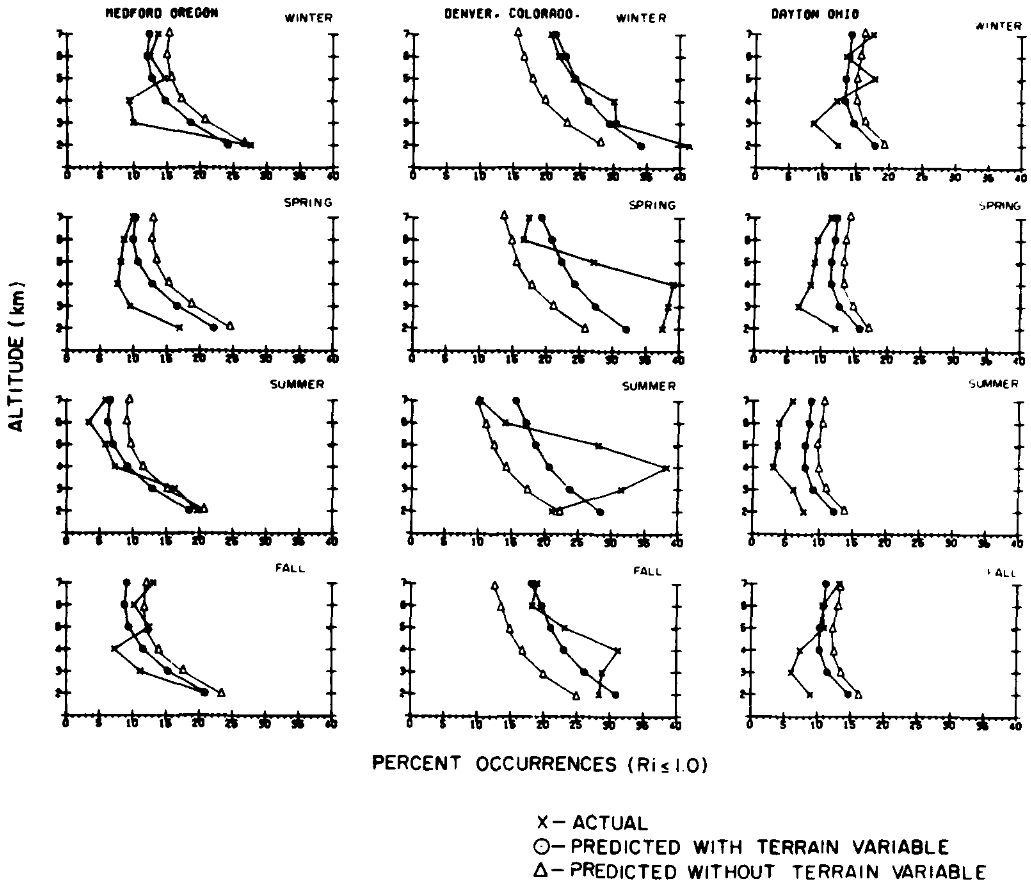

Figure 4. Comparison of Actual Mean Seasonal Occurrences of Turbulence (based on $Ri_c \leq 1.0$) Against Model Predictions (Murphy et al[2]) Without Terrain Variables and Improvements With Terrain Variables Added

4. CONCLUSIONS

a. An independent variable quantifying terrain characteristics in the general region of station location improves turbulence estimates in the 2-7 km altitude range. The accuracy of the estimates are increased by 10% over the model without terrain indicators.

b. Turbulence estimates above 8 km altitude are not significantly improved by knowing the type of terrain.

c. There is evidence to suggest that a more localized effect is present. The average heights of the mountains within a radius of approximately 160 km of a station appears, from a qualitative inspection, to be related to the degree of activity in the 2-7 km altitude region. This, however, is difficult to quantify and further efforts will be applied in this direction.

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